Sediment Accumulation in Tillamook Bay, Oregon: Natural Processes versus Human Impacts

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ABSTRACT

Tillamook Bay on the northern Oregon coast has experienced significant sediment accumulation and shoaling. Analyses show that part of the increased sedimentation was a result of substantial human impacts in the watersheds of the five rivers that drain into the bay. River discharges were enhanced by approximately 13% during the period 1931–1954, when commercial logging and a series of devastating forest fires occurred, compared with discharges in the years after reforestation. Potential annual sediment yields calculated from daily discharges were enhanced by 29% during 1931–1954, but actual yields would have been substantially greater as a result of increased erosion rates because of deforestation. Sand transported by the rivers consists primarily of rock fragments, in contrast to the quartz and feldspar sand carried into the bay from the ocean beach. Surface sediments collected throughout the bay consist, on average, of about 40% sand from the rivers and 60% from the ocean beach. Cores show increasing percentages of beach sand beneath the surface, with evidence for major episodic inputs rather than the higher percentages of river-derived rock fragments that human impacts would have produced. Subduction earthquakes have struck the Oregon coast repeatedly during the past several thousand years; the most recent was in January 1700. The down-core increase in beach-derived sand in Tillamook Bay is from sand transport by the tsunami that accompanied the 1700 earthquake and the deepening of the bay from land subsidence at the time of the earthquake, which permitted more frequent and extensive spit overwash events during storms.

Introduction

Several large estuaries are found along the Oregon coast. Each is associated with a major river that drains the Coast Range. Studies have documented the patterns of sediment accumulation using natural tracers, in particular, mineralogical differences between the river and ocean-beach sands carried into the estuary (see review by Komar and McManus 2000). Those studies involved estuaries that are relatively two-dimensional; they have one major river, and they are accumulating both marine and river sands in proportions that depend on location along the length of the estuary. Furthermore, previous studies did not attempt to relate the estuarine sedimentation to human impacts in the watersheds or to the occurrence of major subduction earthquakes that are known to have generated large tsunami and produced significant land elevation changes along the Oregon coast.

This study is of sediment accumulation in Tillamook Bay, located on the northern Oregon coast about 80 km south of the Columbia River. It is a typical drowned-river estuary but is unusual in that five rivers drain into it: the Trask, Wilson, Tillamook, Kilchis, and Miami (figs. 1, 3). There have been different degrees and types of human impacts in their watersheds, and consequently the area has been the focus of a comprehensive series of investigations to determine how land use practices have affected the water quality, ecology, and processes of sediment delivery and accumulation in the bay. This article is limited to the sedimentation issues.

Since its formation, Tillamook Bay has been accumulating sediment brought in by the rivers and by tides from the ocean beach to the extent that the bay’s present average depth is only 2 m at high tide, and intertidal flats make up some 50% of its surface at low tide. Although much of this sediment fill is the product of natural processes, human impacts during the past 200 yr undoubtedly resulted in increased rates of sediment delivery and accumulation. Those impacts include logging of

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Figure 1. Tillamook Bay and the watersheds of the five rivers that drain into it. The shaded region is the combined area affected by the Tillamook Burns in 1933, 1945, and 1951.

the watersheds and the occurrence of the Tillamook Burns, a series of major forest fires. During this time, beach sand has entered the bay through the inlet at the north end of Bayocean Spit (figs. 1, 3), and a large volume was washed into the bay during 1952–1956, when a breach cut through the south end of the spit.

Area citizens perceive that logging and fires in the watersheds have caused the rapid sediment accumulation in Tillamook Bay, resulting in shoaling that has adversely affected fishing and the commercial oyster industry and also produced increased flooding of the rivers that affects dairy lands and parts of the urbanized area of the city of Tillamook. Thus, the citizens generally are proponents for dredging the bay as a solution to their problems. To address these issues, our study has investigated the sediments in the bay to determine whether human impacts in the watersheds have been the primary cause of rapid shoaling and whether the impacts are reversible.

In this article we report on the analyses of a large number of surface sediment samples from Tillamook Bay, the rivers, and ocean beach to establish the sources of sand entering the bay and the present-day patterns of sedimentation. We report on results from several cores to document changes in the past few hundred years. We characterize the types and sources of sediment accumulating in the bay, especially the relative proportions of river versus ocean contributions, both now and during the past. We also assess the quantities of sediment derived from the rivers and how these quantities differed during the periods of deforestation versus reforestation in order to more directly gauge the extent of human impacts.

The River Watersheds

The areas of the five watersheds are shown in figure 1, and their characteristics are summarized in table 1. The rivers drain the Coast Range mountains that contain Tertiary marine sedimentary formations and volcanic rocks accreted to the continent during plate subduction. The oldest are the Eocene Siletz River Volcanics, which consist of pillow flows of submarine origin, massive lava flows, and sills of basalt. They form the topographic highs and are likely the most important source of sand-sized rock fragments transported into Tillamook Bay. The sedimentary rocks range widely in composition but are predominantly siltstones and mudstones and therefore yield fine-grained sediments.

The watersheds have been greatly affected by human activities, beginning with the arrival of Native
Table 1. Characteristics of the Five Watersheds That Drain into Tillamook Bay

<table>
<thead>
<tr>
<th>River</th>
<th>Drainage [km²]</th>
<th>Percent upland[^a]</th>
<th>Percent burned</th>
<th>Percent logged (1972–1998)</th>
<th>Percent urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miami</td>
<td>93</td>
<td>74.4</td>
<td>33.0</td>
<td>17.0</td>
<td>.30</td>
</tr>
<tr>
<td>Kilchis</td>
<td>168</td>
<td>87.1</td>
<td>52.2</td>
<td>4.7</td>
<td>0</td>
</tr>
<tr>
<td>Wilson</td>
<td>492</td>
<td>92.2</td>
<td>73.6</td>
<td>4.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Trask</td>
<td>451</td>
<td>85.5</td>
<td>49.4</td>
<td>4.5</td>
<td>1.22</td>
</tr>
<tr>
<td>Tillamook</td>
<td>157</td>
<td>32.0</td>
<td>.3</td>
<td>32.1</td>
<td></td>
</tr>
</tbody>
</table>

[^a]: Elevation >500 ft (150 m).

Americans thousands of years ago. There is evidence that Native Americans regularly burned the vegetation of the lowlands surrounding the bay to facilitate access to game and promote the growth of food sources (Winters 1941). For example, an early forest survey found uniform areas of 100- to 200-yr-old trees, indicating the occurrence of fires dating back to the 1600s and before settlement by Euro-Americans (Coulton et al. 1996).

Euro-American settlement first occurred in 1851, and early activities focused on clearing the land near the bay for agricultural use. Levees and dikes were constructed to offer protection from flooding (Coulton et al. 1996). Commercial logging in the steep terrain of the Coast Range became significant during the early twentieth century, with clear-cutting affecting extensive areas of the upper watersheds. A series of major fires during the early to mid-twentieth century, collectively called the Tillamook Burns, represented the most significant impacts in the watersheds and presumably to sedimentation in Tillamook Bay. The first, in 1933, burned nearly 240,000 acres, about half of the total watershed in the bay. Subsequent fires in 1939, 1945, and 1951 brought the total to 355,000 acres. Figure 1 shows the extent of the burned area determined using 1946 aerial photos; this does not include the 1951 fire, which was smaller and re-burned many of the same areas.

Intensive salvage logging in the burned areas began in the 1930s and continued for about 20 yr. The construction of access roads with hundreds of stream crossings is believed to have increased sediment delivery to the bay, mainly by inducing landslides (Mills 1997). The salvage operation also delayed reforestation, which did not begin until 1949. By 1970, reforestation efforts were complete, and with time they have succeeded in restoring the forest cover, which presumably has reduced erosion in the watersheds to more natural levels.

These substantial human impacts undoubtedly resulted in increased sediment delivery to Tillamook Bay. We have attempted to assess that increase and the subsequent return to more normal levels after reforestation through analyses of precipitation data and river discharges and calculations of potential sand transport rates (Styllas 2001). Three time periods are compared: [1] heavily impacted period (HIP), 1933–1954; [2] recovery period (RP), 1955–1976; and [3] normal period (NP), 1977–1998. The 1933 date for the initiation of the HIP corresponds to the first and largest of the Tillamook Burns and also was governed by the first available measurements of discharges in the Wilson River. The 1954 end of the HIP corresponds approximately to the end of salvage logging and the beginning of efforts to reforest the burned areas. The RP represents the time of reforestation leading to the NP, by which time regrowth likely had reduced sediment yields to more natural levels.

Long-term direct measurements of precipitation are available from a gauge operated since 1889 near the city of Tillamook. Average monthly data exist back to 1889, whereas daily records are available since 1961. Figure 2 graphs the annual precipitation beginning with the HIP, whereas table 2 gives the means and standard deviations for the three time periods, which are nearly identical, demonstrating that there were no major shifts in precipitation.

The longest records of river discharges are available from the U.S. Geological Survey gauging stations on the Wilson River (1931–present) and Trask River (1961–1971 and 1996–present). Short records were collected by the Oregon Water Resources Department for the Kilchis, Tillamook, and Miami Rivers (1995–present). The analyses presented here are limited to the Wilson River; the gauge is located 20 km upriver from the bay shore near the foot of the Coast Range. Although the data are limited to daily discharge measurements, Oregon’s Coast Range is not subject to flash flooding. Therefore, the floods typically span several days, so that daily measurements are adequate in our analyses. Analyses of the discharges were undertaken to determine whether they differed between the time periods reflecting degrees of watershed impacts. The daily discharge data were then summed to determine annual water yields [WY, m³/yr] from the wa-
Annual precipitation measured in Tillamook (top), the resulting annual water yields measured in the Wilson River at a USGS gauging station, and their ratios that reflect the impacts of deforestation in the watershed. The bottom graph is the potential annual sediment yields from the Wilson River calculated from the discharge measurements.

The results are graphed in figure 2, and as expected, the general pattern mimics the annual precipitation, particularly during NP after reforestation.

The third graph in figure 2 represents an attempt to normalize the annual water yield, \( WY \), to the annual precipitation, \( P \). If it is assumed that the measured precipitation is representative of the entire Wilson River watershed (which, of course, it is not), then multiplication by the watershed area \( A \) above the gauging site yields \( PA \), which is the annual volume of water \( [m^3/yr] \) delivered to the upper watershed from precipitation. The resulting dimensionless ratio \( WY/PA \) is graphed in figure 2. This normalization of the discharge to the precipitation removes some of the irregularity from the record. It is apparent in both figure 2 and table 2 that during the HIP there was a much larger variability in \( WY/PA \), which became somewhat less during the transitional RP and decreased significantly in the NP. There is also a progressive decrease in the mean values apparent in the downward shift of the curve in figure 2 and mean values in table 2. The ratio of the mean during the HIP to that of the NP is 1.13, a 13% increase in \( WY/PA \) during HIP. We conclude that these changes are a response to the impacts of deforestation and then to the progressive recovery of the watershed as it was reforested. Such increases in river discharges in response to deforestation have been found by other more detailed investigations (e.g., Harr et al. 1982). It is likely that the NP since 1977 is reasonably similar to conditions that existed before Euro-American settlement, before the extreme level of deforestation. The comparison is not quite so simple since fires started by natural processes and Native Americans did occur during earlier times, and the NP has been affected to some degree by recent logging and the presence of roads. However, according to the results in figure 2, during the HIP when logging and fires had their greatest impacts, river discharges were enhanced by the loss of vegetation. The response of the discharge to variations in precipitation was also more erratic, yielding the high variability in the \( WY/PA \) ratio. The substantially lower variability during the NP is evidence for the near recovery of the Wilson River watershed.

Analyses of the river hydraulics were undertaken primarily to serve as the basis for assessments of sediment yields from the watershed, to determine whether deforestation resulted in significant increases and higher rates of sediment accumulation in Tillamook Bay. The evaluation of sediment transport in rivers is difficult, made more so by human impacts in the watersheds that alter erosion rates. The approach we have taken is to evaluate the potential sediment transport and annual yields calculated from the river discharges. In the case of the Tillamook watersheds, this potential transport can be expected to exceed the actual transport since the river channels in the upper watershed have gravel beds with scattered patches of sand. This is evidence that there is limited availability of sand derived from erosion in the watersheds. However, calculations of the potential sediment yields are still informative in reflecting the possible degree of change resulting from deforestation.

We used the stream power approach of Yang (1996) to make the sand transport calculations; details of the analyses can be found in Styllas's work (2001). The model was run for the daily discharge values of the Wilson River, using related hydraulic data such as the channel cross-sectional area, slope,
depth, and width, provided by the U.S. Geological Survey for the gauging station. The daily values of sediment transport were then summed to derive the annual sediment yields, graphed in figure 2 as metric tons per year of sand. The statistics for the three time periods are given in table 2. The high variability of the annual sediment yields reflects the variability in the measured discharges. Of interest, the standard deviation is considerably larger for the HIP, as is the mean value, which is a factor 1.29 greater than the mean for the NP. This provides some measure of the effects of watershed impacts on sediment yields from the Wilson, at least in terms of the calculated potential yields. The actual sediment yields were undoubtedly less than the potential yields because of the limited sand availability. However, during the HIP the deforestation would have resulted in greater rates of erosion, so actual sediment yields would have been closer to the calculated potential yields than during the NP when reforestation reduced erosion in the watershed. This has been shown by more detailed studies in other Coast Range watersheds, where deforestation by clear-cutting resulted in significantly increased sediment yields [Beschta 1978]. Thus, the ratio in the mean values of actual sediment yields between the HIP and NP would have been substantially greater than the 1.29 ratio based on the results in figure 2 and table 2, calculated from the potential yields.

The results in figure 2 and table 2 are only for the Wilson River, where a good record of measured discharges exists. There is a significant gap in discharge data for the Trask River, and there are only very short records of daily discharges for the Kilchis, Tillamook, and Miami Rivers [1995–present]. However, Styllas [2001] found statistically strong correlations between daily discharges on the Wilson with those measured in the other rivers. Using the resulting regression equations he was able to fill the gap in the data for the Trask and to extrapolate the short records from the other rivers to the full period of interest, 1933–1998. Analyses such as those in figure 2 for the Wilson were then undertaken for the other rivers, leading to assessments of potential sediment yields from each watershed, and ultimately the total sediment input into Tillamook Bay. The mean annual input during the HIP was calculated to have been 446,000 tons/yr, decreasing to 336,000 tons/yr during the NP after forest recovery; this difference was a factor of 1.33, approximately the same as found for the Wilson alone. Again, these calculated potential yields are certainly too high, with the actual yields having been lower due to the lack of sand availability in the watersheds. If the 446,000 tons/yr of sand were spread uniformly over the bottom of Tillamook Bay, the equivalent sediment accumulation rate would have been approximately 70 cm/century; as will be discussed subsequently, this value is in good agreement with direct assessments of sedimentation rates. However, as further documented by our study, more than half of the sand accumulating in the bay was derived from the ocean beach, less than half from the rivers. This implies that the actual sand yield from the watersheds during the HIP was less than half the calculated 446,000 tons/yr potential yield.

Tillamook Bay

**Natural Processes and Human Impacts.** Tillamook Bay is separated from the ocean by Bayocean Spit (fig. 3); there is an inlet at its northwest corner controlled by a pair of jetties, a north jetty completed in 1917 and a south jetty constructed during the 1970s. The northern half of the spit is covered by high, vegetated dunes, whereas the southern half is low in elevation and was the site of a major breach in 1952. The breach was closed by the construction of a rock dike in 1956. The Miami River enters the bay at its northeast corner, whereas the four larger rivers—Kilchis, Trask, Wilson, and Tillamook—enter in the southeast corner, where they have formed a delta that has become the center of dairy farming and the location of the city of Tillamook, the largest urban area.

The mean tidal range is 1.7 m, producing a 4.6 × 10⁷ m³ tidal prism, greater than other Oregon estuaries because of the large area of Tillamook Bay.

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**Table 2.** Mean Values and Standard Deviations (in Parentheses) of Precipitation, Annual Water Yields, and Sediment Yields from the Wilson River

<table>
<thead>
<tr>
<th>Period</th>
<th>Annual precipitation [P; m/yr]</th>
<th>Annual water yield [WY; m³/yr]</th>
<th>WY/P × area</th>
<th>Annual sediment yield [SY; metric tons/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavily impacted (1933–1955)</td>
<td>2.24 (.41)</td>
<td>1.10 × 10⁸ (27 × 10⁸)</td>
<td>.117 (.020)</td>
<td>3.11 × 10⁸ (1.29 × 10⁸)</td>
</tr>
<tr>
<td>Recovery (1956–1976)</td>
<td>2.33 (.32)</td>
<td>1.09 × 10⁸ (18 × 10⁸)</td>
<td>.112 (.009)</td>
<td>3.06 × 10⁸ (.91 × 10⁸)</td>
</tr>
<tr>
<td>Normal (1977–1998)</td>
<td>2.25 (.41)</td>
<td>.98 × 10⁸ (24 × 10⁸)</td>
<td>.104 (.008)</td>
<td>2.41 × 10⁸ (.94 × 10⁸)</td>
</tr>
</tbody>
</table>
The estuarine circulation experiences marked seasonal changes because it depends on the discharges of the rivers that respond to the heavy precipitation of the winter versus the dry summer. In a study of several estuaries on the Oregon coast, Burt and McAllister (1958) included measurements of salinities in Tillamook Bay; on the basis of that data and expected seasonal changes in river discharges, they classified the bay as a two-layered stratified system during the winter and as a well-mixed system during the summer. Numerical models have been applied to an analysis of the tides in the bay (Pearson et al. 1996). The circulation and tidal motions are strongly three-dimensional due to the bay’s large area and small depths. The river water primarily enters the bay in its southeast corner, flows toward the north along a channel in the eastern half of the estuary, and then takes a northwesterly course to the inlet. Tidal currents carrying seawater into the estuary mainly follow a separate channel in the western part of the bay. The seaward-flowing freshwater and landward-flowing salt water are separated to a degree by sand bars in the central bay, although there is a complex interfingering of small channels. As will be discussed subsequently, this three-dimensional pattern of circulation governs the transport paths and accumulation patterns of sediments.

Human activities within and surrounding Tillamook Bay affected the patterns of water circulation and sedimentation. As analyzed in the preceding section, deforestation of the watershed increased river discharges during the first half of the twentieth century, which would have affected the circulation and enhanced sediment inputs. Dredging activities have not been particularly extensive. From the late 1800s to 1913, minimal dredging by the Port of Tillamook maintained a shallow-draft channel across the bay. Since 1919, dredging has been limited to the short stretch of channel between the inlet and the small harbor at Garibaldi on the north shore of the bay; most of the dredged sediments were deposited at sea. Between 1929 and 1979, this dredging involved, on average, only 24,000 m$^3$ of sand per year (Chesser 1995) and probably represented a recycling of bay sand between the bay bar and shallow offshore. This was required by the existence of only one north jetty on the inlet until the mid-1970s. Since the construction of the south jetty, the inlet has been maintained mostly by natural scouring.

Although the pair of jetties ultimately reduced the need for dredging, the initial construction of the single north jetty in 1917 resulted in the long-term erosion of Bayocean Spit (Komar and Terich 1977; Komar 1997). The erosion was produced by the northward movement of sand on the beach toward the inlet shoal, which grew substantially following construction of the north jetty. That sand was derived from erosion of the spit to the south, which became progressively narrower until a storm during the winter of 1952 cut a breach that widened during the next 4 yr; this tended to close the inlet to the north. On the basis of the sediment budget considerations that accounted for the volume of sand lost from the ocean beach and eroded spit, it has been estimated that $1.5 \times 10^4$ m$^3$ of beach sand entered the bay through the breach. The breach was sealed with a dike in 1956, and tidal flows reopened the north inlet, but a large bar remained a hazard to ships. Construction of the south jetty during the 1970s stabilized the inlet, making it less of a hazard, and less beach sand is now carried through the inlet into the bay.

**Surface Sediments—Sources and Transport Paths.**

The main goal of our study has been to investigate the sediments that have accumulated in the bay. To accomplish this, 94 surface sediment samples were collected to provide a good spatial coverage of the bay. Samples were also obtained from potential sources, the ocean beach and from the rivers.
upstream from where they enter the bay. Samples from the bay were collected using a small-draft Zodiac-type boat; we were able to access all parts of the bay except for the shallow southeast delta region. The sediment samples were collected with a Forest Peterson–type grab sampler at intervals along a series of east-west transects spanning the bay, supplemented by higher-density sampling in areas of special interest such as channels. Positions of sample sites were established with an accuracy of 5–10 m through the use of differential GPS, using land-based correction data transmitted by the Coast Guard to improve the accuracy of the satellite-based positions. Details concerning the sampling program and analyses can be found in an unpublished report [McManus et al. 1998].

Initially our objective was to relate the quantities of sand derived from the five rivers to different degrees and types of land use practices in their watersheds. The analyses of the sediment samples therefore focused on the possibility of distinguishing between the sands contributed by the individual rivers through detailed analyses of mineral compositions, grain-size distributions, and the use of geochemical tracers. Those efforts were unsuccessful because of the near uniformity of rock types found in the watersheds; all of the rivers yielded rock fragments in all grain-size fractions. This contrasts with the sand entering the bay from the ocean beach, which is composed primarily of quartz and feldspar that contain small quantities of heavy minerals. This distinct compositional difference between the river and beach sands therefore made it possible to assess their relative contributions to the sediment fill of Tillamook Bay.

The bay sediment samples were analyzed using standard procedures [Lewis 1984] that included wet sieving through a 4\( \phi \) (0.0625-mm) sieve to separate the sand from the silt and clay (mud). The surface sediments are predominantly sand (fig. 4); mud accumulates primarily in the southeast delta. Although rivers contribute large quantities of fine-grained sediments, most is flushed through the bay into the ocean. In contrast, sand contributed by the rivers is not effectively moved through the bay and, therefore, dominates sediment accumulation. This conforms to the results of studies in other Oregon estuaries [Komar and McManus 2000].

The separated sand fraction was dried and split to yield 100–200-g subfractions and sieved at 0.25\( \phi \) intervals, yielding detailed grain-size distributions that made it possible to detect individual grain-size modes. We believed that they might represent different sources and transport paths. Each sieve fraction was examined under a binocular microscope to determine the percentages of rock fragments (RF) derived mainly from the rivers, the quartz and feldspar (Q/F) washed or blown into the bay from the ocean beach, and heavy minerals (HM); 300 individual grains were classified for each sieve fraction. This permitted detailed analyses of the grain-size distributions of the RFs versus the Q/F in each sample as illustrated in figure 5 for a sample collected from the middle of the bay where each of the components is present.

The grain-size distributions of the compositional components in each sand sample were established. Their summations yielded the relative proportions of river-derived RFs versus the Q/F carried into the bay from the ocean beach. The resulting patterns for the RF and Q/F percentages within Tillamook Bay are shown in figures 6 and 7. The two patterns are nearly an inverse since these are the two dominant components; the HM generally represent minor percentages. As expected, the highest RF contents are found near the river mouths, and more generally this fraction dominates the eastern half.

Figure 4. Classification of the surface sediment samples in terms of the proportions of mud [clay plus silt] versus sand.
Figure 5. Analysis of a surface sediment sample from Tillamook Bay in terms of (A) the grain-size distribution of the entire sample; (B) the compositions of each sieve fraction in terms of the percentages of quartz and feldspar (Q/F), rock fragments (RF), and heavy minerals (HM); and (C and D) the grain-size distributions of the separated RF and Q/F components derived from the product of (A) and (B).

Figure 6. Percentages of rock fragments in the surface sediments derived from the rivers of the bay, following the main channel that serves as the primary path for freshwater movement, eventually becoming the ebb-dominated channel through the inlet. There is one outlier sample with a high RF value in the southwestern part of the bay near the 1952–1956 breach through Bayocean Spit; it likely has been contaminated by RFs derived from the riprap dike constructed to close the breach. Otherwise, RFs form <25% of the sand in the western half of the bay, where Q/F is otherwise dominant (fig. 7).

The Q/F percentages in the bay samples reflect the significance of processes that transport the beach sand into the bay. As expected, this contribution is close to 100% near the inlet at the north end of Bayocean Spit (fig. 7) but is also important in the bay sand to the south along the full length of the spit; these follow the course of the dominant flood tide channel that would be the route of beach sand movement to the south from the inlet. Before the 1930s and the introduction of European beach grass that now thickly covers the spit, beach sand blown into the dunes that cover the spit was probably also carried into the bay. As expected, the >1 million m³ of beach sand that was washed into the bay as a result of the 1952–1956 breach at the south end of the spit is dominated by Q/F. The inferred paths of sediment transport as determined from the compositions of the surface sediments are summarized in figure 8. River-derived sand (RFs) primarily enters the bay in the delta region of the four largest rivers [its southeast corner]; the Miami River in the northeast corner makes a relatively small addition. The main northward transport of the riverine sand is denoted by the trend of the largest arrows for the RFs and follows the large channel in the eastern half of the bay. Beach sand (Q/F) concurrently enters the bay primarily through the inlet at the north and is carried along the bay’s tidal channels. The central part of the bay is the
primary zone of mixing of river- and beach-derived sands.

The results from the analyses of the surface sediments can be incorporated into a sediment budget for the proportions of river-derived versus beach-derived sands that are accumulating in Tillamook Bay. These are obtained by integrating the percentages of RFs (fig. 6) and Q/F (fig. 7) across the area of the bay. If the small quantities of HM are equally allotted to the two sources, the resulting sediment budget indicates that about 60% of the sand fill is Q/F derived from the ocean beach, whereas the 40% balance is RFs contributed by the rivers. If the finer-grained sediments (clay and silt) are included in the budget and derived from the rivers, the river contribution is increased to roughly 50%; the ocean beach contributes the other 50%.

The separation of the RF, Q/F, and HM compositional components in the bay sediment samples (fig. 5) also permitted detailed analyses of their respective grain-size distributions (Styllas 2001). We believed it might provide evidence for the proportions of RFs contributed by the individual rivers, with each supplying distinctive grain-size modes whose movement could be followed through the bay. Although considerable effort was directed toward accomplishing this through the separation of the RF grain-size distributions into series of modes and also by undertaking a factor analysis of the grain-size distributions, all attempts failed to link the modes or factor end members to specific rivers. The spatial patterns of the RF modes appear to be controlled instead by the hydraulics of the tides and currents in the bay—the coarsest modes are found primarily in the northern part of the bay near the inlet and the finer-grained modes are found in the southeastern delta region (Styllas 2001). The RFs supplied by the rivers enter the bay primarily in the southeast corner. Their subsequent dispersion with the coarsest modes ending up farthest from the river mouths demonstrates that the energy levels of estuarine processes are controlling their areas of deposition. This is confirmed by analyses that demonstrated that the Q/F grain sizes carried into the bay from the ocean beach are sorted into the same spatial patterns as the RFs (Styllas 2001).
The Down-Core History of Sediment Accumulation. Understanding the long-term accumulation of sediments in Tillamook Bay and changes in river versus ocean beach inputs through time required the collection and analysis of cores. These were obtained from nine sites across the central bay using a standard gravity corer deployed from the Oregon State University ship RV Sacajawea. Eight of the nine cores were in the length range 1.5 ± 0.25 m, and the ninth was 0.5 m.

Reflectance measurements were made to determine whether dark layers, possibly produced by the Tillamook Burn fires, might be present. The analyses used an Automated Reflectance Spectroscopy Logger that is more sensitive than the human eye in detecting color changes [Mix et al. 1992]. The Logger measures the reflectance spectra in the ultraviolet, visible, and near-infrared bands along the lengths of the freshly split cores. In spite of this level of sophistication, while there was the occasional spike in color change, there were no distinct signatures attributable to material associated with the fires [McManus et al. 1998]. This absence does not preclude the likelihood of a period of increased sedimentation; it is possible that charred wood from the fires was flushed through the estuary, or if any did accumulate it was subsequently dispersed by the burrowing activities of organisms or by estuarine currents.

Information on shoaling and deposition rates of sediments in Tillamook Bay is available from two previous studies. Glenn [1978] investigated the early history of sedimentation by drilling long cores that achieved depths of about 30 m, reaching the Pleistocene pre-estuarine deposits. His assessments of sedimentation rates were based on 14C dates of extracted organic carbon, indicating that between about 7000 and 8000 yr B.P., soon after the formation of the estuary by the rising sea, rates were on the order of 200 cm/century. After about 7000 yr B.P., the rates dropped to approximately 20–30 cm/century. A graph of dates versus sample depths yields a curve that parallels the general curve of rising sea level, indicating that the decreasing rates of sedimentation with time were in part a response to sea-level controls. Of relevance to our study, the 20–30-cm/century rates found by Glenn can be viewed as the “natural” rates of sediment accumulation before the arrival of Euro-Americans. His analyses did not extend to the near-surface sediments, of interest to our study, that might have been affected by their impacts.

Also relevant to estimates of sedimentation rates during the past 2 centuries are analyses by Bernert and Sullivan [1998] of bathymetric surveys in Tillamook Bay undertaken in 1867, 1957, and 1995. There are potentially large errors in the bathymetric maps and in the inferred depth changes because of a variety of problems such as improving abilities to accurately position survey locations and make depth measurements and the possibility that there have been changes in datums. Comparing mean depths below the MLLW tidal datum, R. Garono (pers. comm., 1998) derived mean-depth changes between surveys, which we further modified to account for increased mean sea levels during the intervening years. For the entire span of time covered by the bathymetric surveys, 1867 to 1995, the average sedimentation rate was found to be on the order of 50 cm/century. Individually, the three surveys demonstrate that a higher rate of sedimentation occurred between 1867 and 1954—the average having been about 70 cm/century—with a lower but indeterminate rate between 1954 and 1995.

We attempted to measure sedimentation rates based on 14C dating of shells found in the cores and measurements of Pb-210 profiles; the details of those efforts can be found in our unpublished report [McManus et al. 1998]. Shell fragments found in two cores at 100-cm and 99-cm depths in the sediment were dated at A.D. 1460 and A.D. 1720, yielding sedimentation rates of 20 and 43 cm/century. These are reasonably consistent with the results of Glenn [1978] and Bernert and Sullivan [1998]. Pb-210 profiles were measured for five cores, yielding distributions where activities decrease exponentially with depth, approaching a constant value. In Tillamook Bay the dominant factor controlling the distribution of Pb-210 is mixing by burrowing shrimp and some transport by estuarine currents. As a result, neither the sediment mixing rate nor the accumulation rate can be uniquely determined from the measured Pb-210 distributions. Our approach was to generate best-fit agreement between the measurements and mathematical relationships for sediment accumulation and mixing and to apply the model to various depth ranges within the sediment. The most reasonable results were obtained by limiting the analysis to measurements below a depth of 75 cm, indicating that burrowing by shrimp was minor below that level. This restriction yielded sedimentation rates on the order of 30 cm/century, again consistent with the other measurements of sedimentation rates.

The results of our measurements of deposition rates of sediments in Tillamook Bay, together with those of Glenn [1978] and analyses by Bernert and Sullivan [1998] of the bathymetric surveys, yield a reasonably consistent history of sediment accumulation. The short cores analyzed in our study
roughly represent the past 500 yr of sediment accumulation, indicating average rates on the order of 20–40 cm/century, as found by Glenn. The analyses of bathymetry changes since 1867 yield an average sedimentation rate on the order of 50 cm/century, but perhaps with a higher rate (70 cm/century) between 1867 and 1954, and a marked decrease since 1954. Based on sedimentation rates alone, one might conclude that the higher rate between 1867 and 1954 was a result of increased sediment yields from the watersheds during the HIP caused by deforestation following the arrival of Euro-Americans. This period would also include the introduction of large quantities of beach sand into the bay during the breaching of Bayocean Spit [1952–1956]; the reduced shoaling between 1954 and 1995 might reflect the lower sediment input volumes during the recovery and normal periods. However, our analyses of the down-core sediment compositions indicate that this simple interpretation does not fully explain the history of sediment accumulation.

The down-core analyses of the river-derived versus ocean beach sands were based on geochemical analyses rather than on grain counts as undertaken for the surface sediments. The geochemical analyses were initiated in the hope that there would be chemical tracers of sands derived from the individual rivers, making distinctions between their contributions possible. Even with measuring minor chemical elements, we were unable to positively distinguish between sands contributed by the individual rivers. However, there are marked geochemical differences between the river and ocean beach sands, which is not surprising considering their contrasting mineralogy. We decided to base the down-core sediment source determinations on geochemical analyses that provide accurate assessments and were not as time consuming as the grain counts. The procedures included dissolving (“digesting”) the entire sediment sample, performing elemental analyses using a Liberty 150 Emission Spectrometer to measure the Al, Ba, Ca, Fe, Mn, and Ti contents, and measuring trace elements with a VG PlasmaQuad 2 ICP-MS [McManus et al. 1998]. After a review of the results, we decided to focus on the titanium [Ti], a major element in the weathered volcanic sediments of the Coast Range, the material forming the sand-sized rock fragments analyzed by the grain counts. In contrast, the ocean beach sand represents a low Ti source.

We conducted geochemical analyses on sediment samples from the ocean beach and rivers and for 37 surface sediment samples collected in the bay—different samples than used in the grain-count analyses. The results were essentially the same for the spatial patterns of river-derived [high Ti] versus beach-derived [low Ti] sediments, supporting our interpretation presented in figure 8 for the transport paths and areas of sediment accumulation. The geochemical distinctions between the sediment sources then served as the foundation for the down-core analyses to determine how the relative contributions from the rivers and ocean beach varied during the past few hundred years. Funding constraints limited analyses to five of the eight long cores, three from the south-central bay and two from the margin of the eastern-bay channel. The results are shown in figure 9 for changes in the
Al : Ti ratios down core; the higher ratios correspond to increases in the beach source relative to the rivers. Cores 5 and 6 from the south part of the bay have low Al : Ti ratios, demonstrating that throughout the past this area has been dominated by river sediments, just as it is today. Core 7 from the eastern-bay channel documents a significant increase in the Al : Ti ratios at depth within the sediment, indicating that during the earliest stage in the record the ocean beach was a substantially more important source of sediment to bay filling along the course of this important channel, but there has been a progressive shift toward riversupplied sand being dominant at that site. Located within the main channel of sediment movement through the bay, core 7 should have been particularly sensitive to changes in relative sediment contributions from the ocean beach versus the rivers through time. The documented change must reflect a significant environmental shift that spanned hundreds of years.

Core 10 is the closest to Bayocean Spit (fig. 9), and its profile is of particular interest. It shows extreme variations in the Al : Ti ratios and a strong dominance of ocean beach sediments at the 42- and 82-cm levels in the core, the latter being essentially 100% beach sand. The site of this core was affected by the historic 1952–1956 breach of the spit and the introduction of beach sand to the surface sediment. This suggests that the much higher Al : Ti ratios found at the 42- and 82-cm levels are records of earlier, prehistoric breaching events that were substantially larger and longer lasting than the 1952–1956 breach.

The analyses of the down-core sediment compositions demonstrate that during the past few hundred years, beach sand was a more important contributor to bay filling than was sand derived from the rivers. The analyses of the surface sediment samples presented earlier established that about 60% of the sand came from the ocean beach and 40% came from the rivers. Although too few cores were collected and analyzed to establish a sediment budget back through time, during the past few hundred years as recorded in the cores, the beach contribution represented closer to 75% and progressively declined to the present proportions. This higher proportion of beach sand in the past argues against a conclusion that the higher rates of sediment accumulation and shoaling between 1867 and 1954, found from the bathymetric surveys and confirmed by our measurements, were due mainly to increased sediment yields from the river watersheds caused by deforestation.

Our interpretation is tentative because it is based on only a few cores. We conclude that the greater quantities of beach sand that entered Tillamook Bay during the past few hundred years resulted from the major subduction earthquake and tsunami that occurred in January 1700. The Oregon coast is located within a zone of active plate convergence and subduction between the Juan de Fuca and Gorda ocean plates that are moving eastward toward the continent. These plates are subducted beneath the North American plate. There have been no historic subduction earthquakes since settlement by Euro-Americans, but there is evidence that earthquakes have occurred in the more distant past. This evidence includes investigations of estuarine marshes buried by sand layers, a sequence that indicates that portions of the coast have abruptly subsided at times of earthquakes, followed by extreme tsunami that swept over the area to deposit the sand (Atwater 1987; Darienzo and Peterson 1990; Atwater and Yamaguchi 1991; Darienzo et al. 1994). The exact time of the most recent earthquake was established by Satake et al. (1996) and was deduced from the arrival of the tsunami on the coast of Japan. It occurred on January 26, 1700, and was estimated to be approximately magnitude 9, based on the size of the tsunami that reached Japan.

The presence of sand layers in the bays and estuaries along the Oregon and Washington coasts documents that the tsunami in 1700 covered marshes and carried sand inland up the river channels. In Tillamook Bay the tsunami would have washed over the southern half of the spit, transporting large quantities of beach and dune sand into the bay. The strain released by the earthquake resulted in the subsidence of the bay and its surroundings by about 1 m (Peterson et al. 2000); this would have had a profound effect on sediment accumulation that could have persisted for more than a century. The lowered level of the spit would have permitted frequent overwash and breaching events during major storms. The record from core 10 shows episodic inputs of beach sand into the bay and is interpreted as being the product of such events. The general deepening of the bay would have resulted in increased quantities of beach sand carried through the inlet to be permanently deposited in the bay, yielding the record found in core 7 adjacent to the eastern-bay channel that would have been a major route of sediment transport. The general subsidence of the land relative to the sea would also have resulted in the regrading of the rivers with riverine sands accumulating in the channels. Thus, the subduction earthquake likely reduced river-derived sand inputs into Tillamook
Bay, further accounting for the higher percentages of beach-derived sand.

Conclusions and Discussion

An interpretation of the history of sediment accumulation in Tillamook Bay is presented in figure 10 by way of a summary of the results of this study. The main event depicted is the effect of the subduction earthquake in 1700, which produced a spike in the input of beach sand caused primarily by the tsunami that accompanied the earthquake. The earthquake produced a deepening of the bay due to the general subsidence of the coast, which would have resulted in a prolonged period of beach sand entry and accumulation. This is depicted by the roughly exponential decrease in beach sand after the earthquake but with multiple spikes due to spit overwash and breaching events that would have been frequent due to the lowered elevation of the spit. The most recent spike is from the 1952–1956 breach of Bayocean Spit caused by the construction of the north jetty on the inlet that resulted in the erosion of the spit. Another important perturbation in the graph is the increase in river-derived sand that occurred after settlement by Euro-Americans and their impacts in the watersheds. This increase is shown beginning with their arrival in 1850, and especially from 1900 to 1950, when deforestation was greatest, including the HIP analyzed in this study. Here we have had to be speculative in that while our analyses of river discharges and sediment transport rates point to significantly increased sediment yields from the watersheds due to human impacts, the documentation in the bay of those increased yields remains incomplete. In part this is because our analyses of the sediments have been limited to cores collected in the central part of the bay below the MLLW tide level, whereas the study by Bernert and Sullivan (1998) of bathymetric changes indicated that most of the historic shoaling and accretion occurred in shallow water along the bay's margins, especially in the southeast delta region. Also, human activities have partly mitigated against those that produced increased sediment yields from the rivers. During the late nineteenth century, levees built of sand and gravel extracted from the river channels were constructed along the lower reaches of the rivers. It may be that much of the sand derived from the increased erosion of the upper watersheds after deforestation was deposited in the artificially deepened channels. Although the model of figure 10 needs to be confirmed by further data collection in Tillamook Bay, it accounts for the expected influences of the subduction earthquake in 1700 and human impacts in the watersheds. It also explains to a reasonable degree the variations through time in sedimentation rates and, in particular, the varying proportions of beach versus river-derived sands found in the bay sediments.

The primary motivation for this study was to determine the extent to which human impacts increased shoaling rates in Tillamook Bay. The expectation was that this has been significant because of the extreme degree of deforestation during the late nineteenth to mid-twentieth century caused by commercial logging and the Tillamook Burns that denuded much of the watershed. In addition, the breaching of Bayocean Spit from 1952 to 1956 caused by the construction of a jetty at the bay's inlet introduced more than a million cubic meters of beach sand into the bay. In view of that recent event, our result that 60% of the surface sand in
the bay is derived from the beach and only 40% from the rivers did not come as a surprise. It was surprising to discover that the proportion of beach sand increased down-core, where we had expected to find higher quantities of river-derived sand produced by increased watershed yields at the time of deforestation. This discovery led to the conclusion that the subduction earthquake in 1700 has been important to the sediment filling of Tillamook Bay. In hindsight, we should not have been surprised by this result in view of the extreme nature of that tectonic event, an earthquake estimated at magnitude 9 that generated a huge tsunami that swept well inland along most of the Oregon coast, transporting and depositing ocean beach sand. Adopting a long perspective, although the impacts of humans in producing increased rates of shoaling in Tillamook Bay during the past 150 yr have been important, the impacts of that subduction earthquake 300 yr ago appear to have been greater.

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